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Cavity enhanced second-harmonic generation of a cw blue (440 nm) diode laser output is achieved using a nonlinear crystal BBO in an external, high finesse ring cavity. Simulations show that under ideal beam conditions the generation of ~30 mW UV power is possible with 250 mW of incident power when design parameters are optimized. Output is observed at 220 nm at power levels that currently do not exceed a few uW. Shortcomings of the present laser and frequency doubling resonator such as the lack of suitable dichroic mirrors, astigmatic beam

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NAME	PERCENT_SUPPORTED
Amarin Ratanavis	0.25
Duy Nguyen	0.15
Shaheed Rahim	0.10
Satish Kasarla	0.25
FTE Equivalent:	**0.75**
Total Number:	**4**

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Names of Faculty Supported

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Wolfgang Rudolph	0.05	No
FTE Equivalent:	**0.05**	
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CW UV radiation through second-harmonic generation of blue diode laser output

Final Report (04/20/2009 – 01/19/2010)

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Statement of the problems studied

The goal of the project was to demonstrate a compact cw UV (220 nm) laser source by cavity enhanced second harmonic generation of a cw blue diode laser output in a suitable nonlinear crystal.

Abstract

Cavity enhanced second-harmonic generation of a cw blue (440 nm) diode laser output is achieved using a nonlinear crystal BBO in an external, high finesse ring cavity. Simulations show that under ideal beam conditions the generation of ~30 mW UV power is possible with 250 mW of incident power when design parameters are optimized. Output is observed at 220 nm at power levels that currently do not exceed a few μW. Shortcomings of the present laser and frequency doubling resonator such as the lack of suitable dichroic mirrors, astigmatic beam from the diode laser and imperfect mode matching – are currently being addressed.

CW UV radiation through second-harmonic generation of blue diode laser output

Here we report on the generation of UV radiation by frequency doubling of a cw blue (440 nm) diode laser in an external cavity.

1. Principle

The principle is based on resonant cavity enhanced second harmonic generation. For a high Q optical cavity, the intra-cavity circulating power can be very high if the incident light is resonant and mode-matched to the cavity. Due to high intra-cavity circulating power, the generated second harmonic by placing a crystal in the cavity could be substantial, even if the process converts only a small fraction of the circulating optical power.

2. Design aspects

For efficient second harmonic generation (SHG), the cavity has to be designed such that (i) cavity has high finesse, (ii) the coupling of the incident light in to the cavity is optimized (impedance matching), (iii) the incident pump field has to be mode matched with that of the intracavity field, (iv) the nonlinear crystal parameters such as crystal length, phase matching etc. have to be optimized. We have designed our cavity to take care of the above aspects as detailed below.

2.1. Optimum coupling

Consider a cavity consisting of four mirrors M1, M2, M3 and M4 and an SHG crystal as an intracavity element. The intracavity power enhancement at resonance neglecting loss due to SHG conversion is given by [1]

$$\eta \equiv \frac{P_c}{P_i} = \frac{1 - R_1}{\left(1 - \sqrt{T_c^2 R_1 R_2 R_3 R_4}\right)^2}\ , \qquad \ldots\ldots\ldots\ldots(1)$$

where P_c is the intracavity circulating power and P_i is the incident power. $R_{1..4}$ are the reflectivity of the mirrors M1…4, and $T_c = (1 - R_c)$, where R_c is the reflectivity of the crystal surface.

Figure 1 shows the cavity enhancement as a function of reflectivity R_1 of the in-coupling mirror M1. For the simulations, the reflectivity of mirrors M2, M3 and M4 was chosen to be ~99.5% and the crystal surface reflectivity was set at 0.25%. It can be seen that optimum reflectivity R_1 of the incoupling mirror is about 98%.

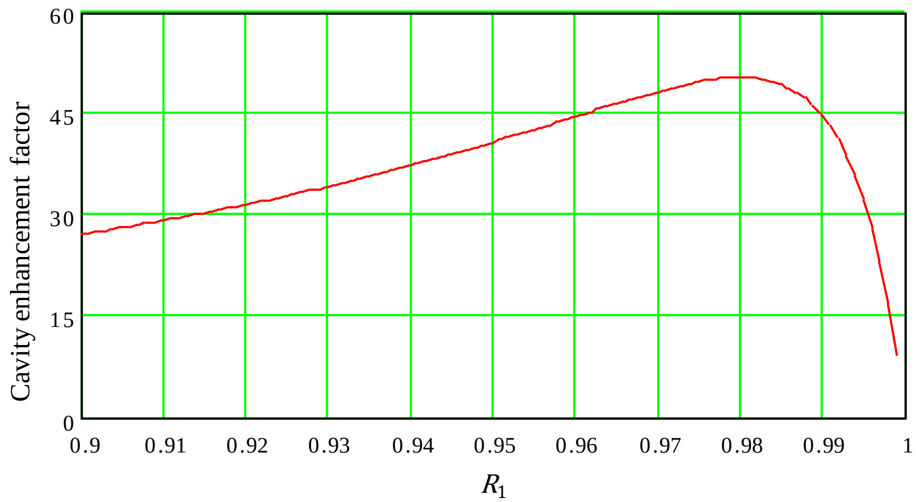

Fig. 1: Expected cavity enhancement as a function of the reflectivity of the incoupling mirror

2.2. Optimum focusing condition for efficient Second Harmonic Generation

The generated second harmonic power is proportional to the square of the incident intensity. Hence one would normally think that it is better to use the smallest achievable spot size for the incident beam. However, it can be shown that this is not the case. Too small a spot size will lead to large walk-off of the interacting beams thus reducing the efficiency, while too large a spot size will lead to lower efficiency due to reduction in the input intensity. For a Gaussian beam, the optimum focusing conditions for efficient second harmonic generation have been laid out by Boyd and Kleinman [2]. The highest efficiency occurs when the incident laser beam is focused so that the beam waist is located at the center of the crystal and for a particular ratio of crystal length to confocal parameter, see below.

The SHG conversion efficiency is given by [2]

$$\Gamma = \frac{2\omega_1^2\, d_{\mathrm{eff}}^2 k_1}{\pi\varepsilon_0 n_1^2 n_2 c^3} L_c\; h(\sigma, B, \xi)\,, \qquad \text{..........(2)}$$

where ω_1 is the fundamental frequency, d_{eff} is the nonlinear coefficient, n_1 is the refractive index at the fundamental frequency, n_2 is the refractive index at the second harmonic, k_1 is the wave vector for the incident beam, L_c is the crystal length. $h(\sigma, \beta, \xi)$ is the Boyd Kleinman focusing factor with walk-off parameter B, wave vector mismatch parameter σ, and crystal length to confocal parameter ratio ξ, and is given by [2]

$$h(\sigma, B, \xi) = \frac{1}{4\xi}\int_{-\xi}^{\xi}\int_{-\xi}^{\xi} \frac{\exp[i\sigma(m-n)]\,\exp[(-B^2(m-n)^2/\xi)]}{(1+im)(1-in)}\, dm\; dn\,, \qquad \text{.........(3)}$$

where $B = \rho\sqrt{L_c k_1}\,/2$, $\sigma = \; b\,\Delta k/2$, and $\xi = L_c/b$. Here, ρ is the walk-off angle, $\Delta k = 2k_2 - k_1$ is the phase mismatch, and b is the confocal parameter related to beam waist w_0 through the relation $b = k_1 w_0^2/2$. For a given crystal, the parameter $h(\sigma, \beta, \xi)$ has to be maximized with respect to ξ in order to achieve maximum efficiency. Maximizing this term [3] will give the optimum spot diameter on the crystal. Figure 2 shows the optimum spot diameter ($2w_0$) for various crystal lengths. For the calculations, we chose a BBO crystal cut at $\theta = 64.6^{o}$ for type-I SHG. The d_{eff} parameter of the crystal is 1.78 pm/V at the design wavelength of 446 nm. The beam walk-off angle ρ is estimated to be around 70 mrad using the SNLO program [4]. Maximizing the parameter h in Eq. (3) gives a crystal length to confocal parameter ratio of about 1.4. It can be seen from Fig.2 that the optimum spot diameter for a 10 mm crystal is about 35 μm.

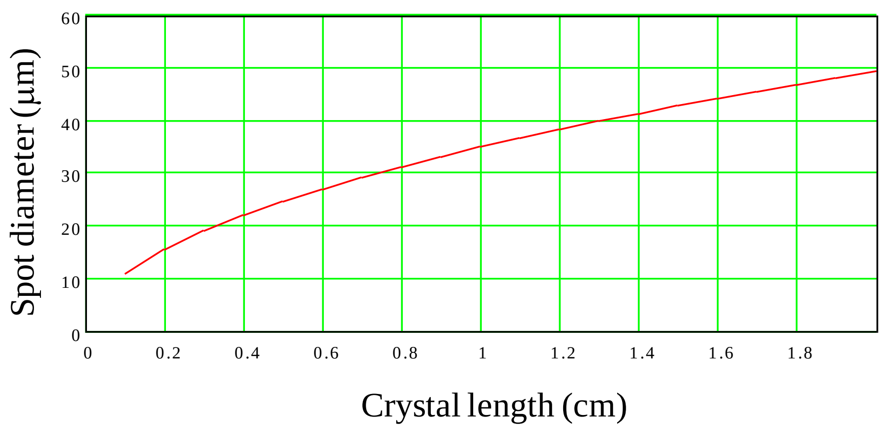

Fig. 2: Optimum spot diameter inside the crystal as a function of crystal length.

2.3. Conversion efficiency with pump depletion

Kozlovsky et. al [5] extended the theory of Ashkin and Boyd [1] of cavity enhanced second harmonic generation by taking into account the depletion of the fundamental wave due to the frequency doubling process. The additional `loss' factor due to second harmonic generation can be described by including an additional crystal transmission term $t_{SH} = (1 - \Gamma \times P_c)$ in Eq. (1). Here, Γ is the SHG conversion efficiency given in Eq. (2). It has to be noted that this additional loss factor is a nonlinear function of incident power.

Figure 3 shows the cavity enhancement factor as a function of input incident power for a crystal of 10 mm length for input coupling of 98%. For comparison, the enhancement factor without the SHG conversion losses also is given.

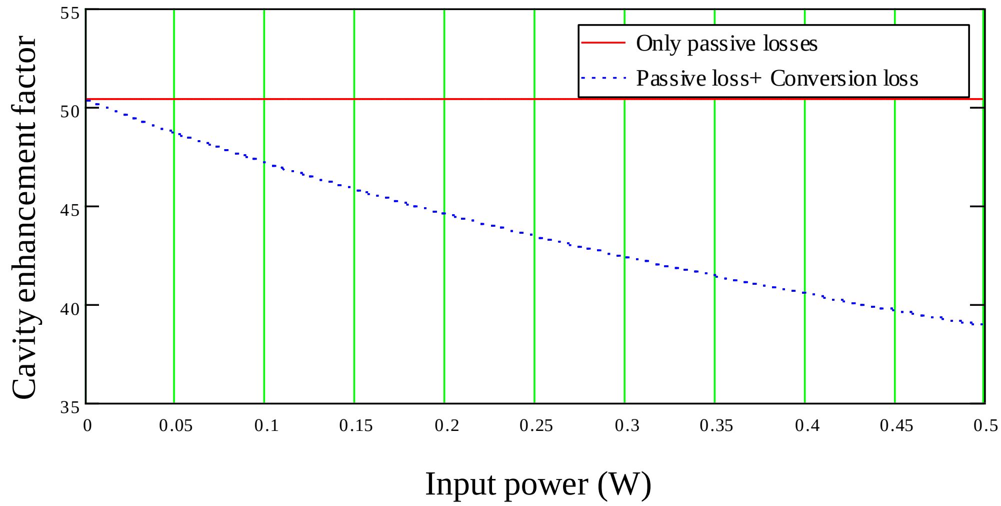

Fig. 3: Cavity enhancement factor as a function of input power with and without pump depletion.

Figure 4 shows the expected second harmonic power for a 10 mm BBO crystal as a function of incident power for optimal coupling and focusing.

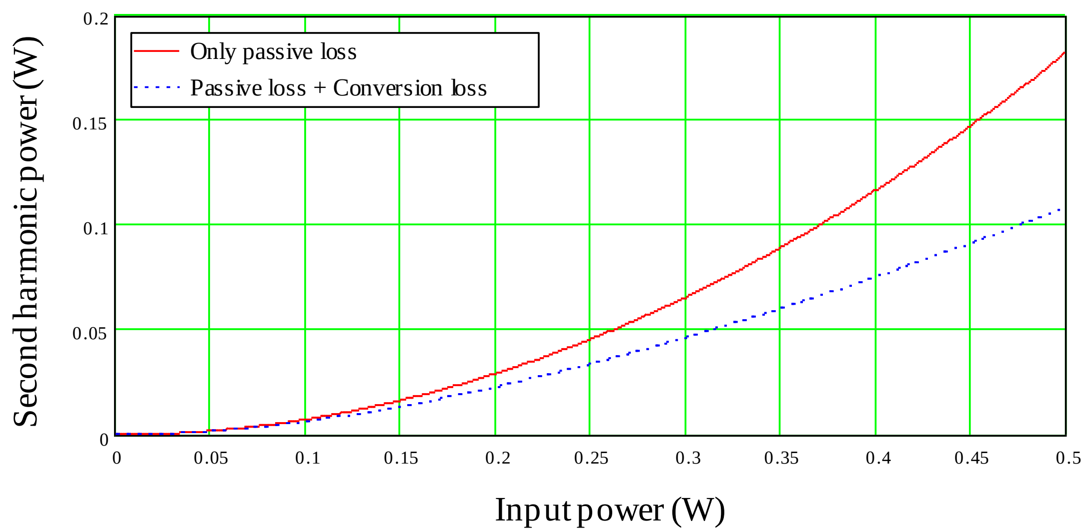

Fig. 4: Expected second harmonic power as a function of fundamental power for an optimized cavity.

2.4. Choosing optimum cavity parameters

The layout of the cavity is shown in Fig. 5. The cavity length and mirror curvatures where chosen to produce the optimum spot diameter of 35 microns at the center of the 10 mm crystal. The mirror M1 (in-coupling) mirror had a reflectivity of 98% while other mirrors had a reflectivity of 99.5%. Figure 6 shows the theoretical intra-cavity beam radius at various distances z from the input coupling mirror for optimum second harmonic generation.

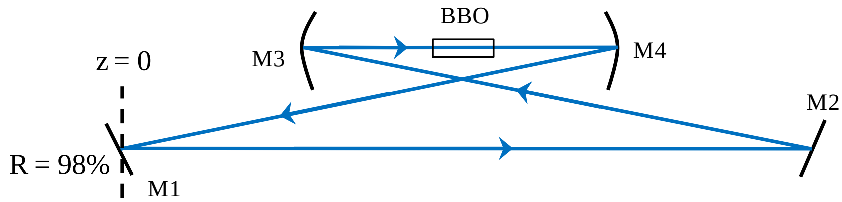

Fig. 5: Layout of the cavity considered in the simulations.

Optimum parameters for the cavity are tabulated below:

Table I. Cavity parameters for efficient second harmonic generation through resonant enhancement.

Beam diameter (μm) at various positions	M1	M2	M3	M4	Center of crystal	Center of M1-M2
	430	430	654	654	35	360
Distances (cm)	M1-M2	M2-M3	M3-M4	M4-M1	M3-crystal	Center of M1-M2
	30	19.4	8.5	19.4	4.25	15

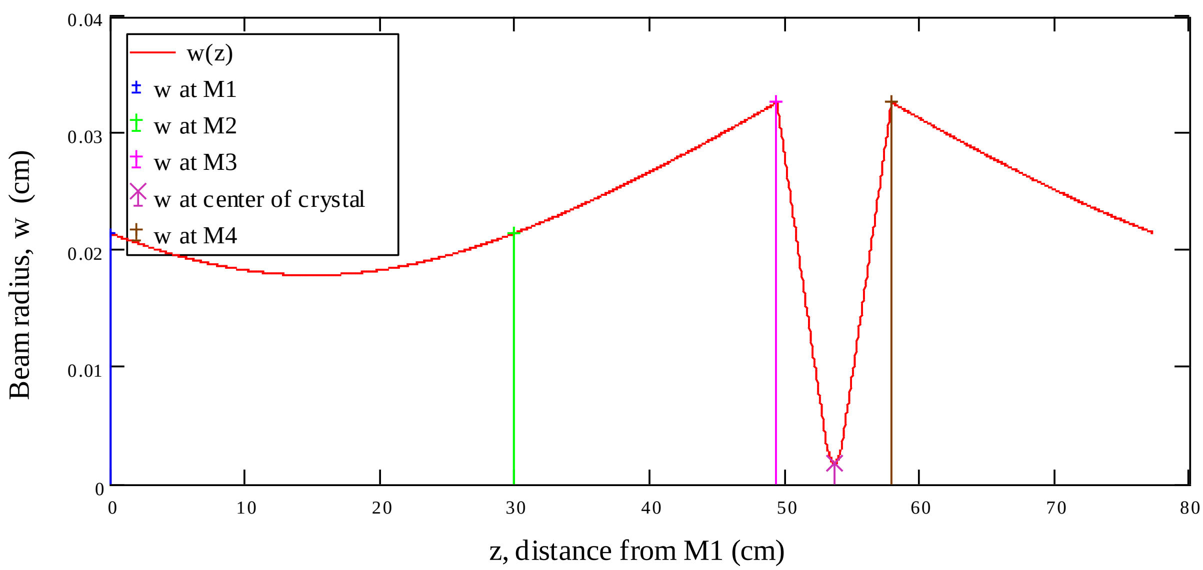

Fig. 6: Calculated intra-cavity beam radius at various locations in the cavity.

3. Experiment and results

The schematic of the experimental setup is shown in Fig. 7. A blue laser diode (NDB7112, 420 mW) was acquired from Nichia Corporation (Japan) and mounted by Power Technology, Inc., Little Rock, AR [LDCU8/9160]. We set up an external cavity consisting of a grating (Thorlabs GR13-1208, 1200 lines/mm, 750 nm blaze wavelength) to force the laser to oscillate in single-frequency mode. Without external cavity, the laser typically emits a power of 420 mW at 440 nm. The feedback provided by the grating was about 2%. The diode faces were not AR coated because we were unable to find a vendor to provide the AR coating on the diode.

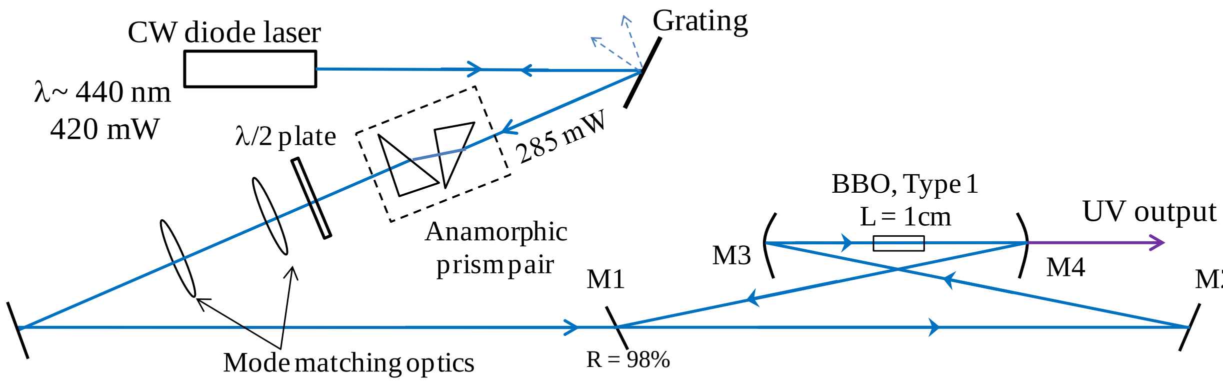

Fig. 7: Schematic of the UV generation by cavity enhanced SHG of blue diode laser.

The M^2 values of the diode laser without the external cavity arrangement (no grating output coupler) was measured using an f = 200-mm lens AR coated at 400 nm. The power was attenuated by using the front surface reflection off a sapphire prism. A Newport LBP-4-USB beam profiler was used to record beam diameters at various distances. Figure 8 shows the measured beam diameters and the calculated M^2 parameter. M^2_{hor} ~ 5.5, M^2_{ver} ~ 2.7. The expression that was used in the fitting is $w(z, w_0, \mathrm{M}^2) = w_0\sqrt{1 + \frac{\lambda\, z\, \mathrm{M}^2}{(\pi w_0^2)^2}}$, where w_0 is the 1/e^2 radius of the real beam (i.e. not diffraction limited). The mode structure of the diode laser was measured with a scanning Fabry-Perot interferometer (SFPI). An f = 400 mm cylindrical lens was used to collimate the horizontally strongly divergent diode laser beam, before it was incident on the SFPI.

Figure 9 shows the SFPI scans with and without grating feedback. The two high peaks within one ramp are separated by about 220 nm = λ/2, calculated with the ~490 nm/V value extracted from the calibration using the He:Ne (0.45V x 100 x 490 nm/100V = 220 nm). The origin of the two double-peaks in Fig.9(b) is not clear; it may be a result of “aliasing” due to the too small value of the free spectral range of the SFPI or higher-order transverse modes. Another reason could be that operation of the diode laser was disturbed due to back reflection from the Fabry-Perot. These experiments will be repeated with a recently acquired Faraday isolator between diode laser and Fabry-Perot to prevent feedback to the diode laser.

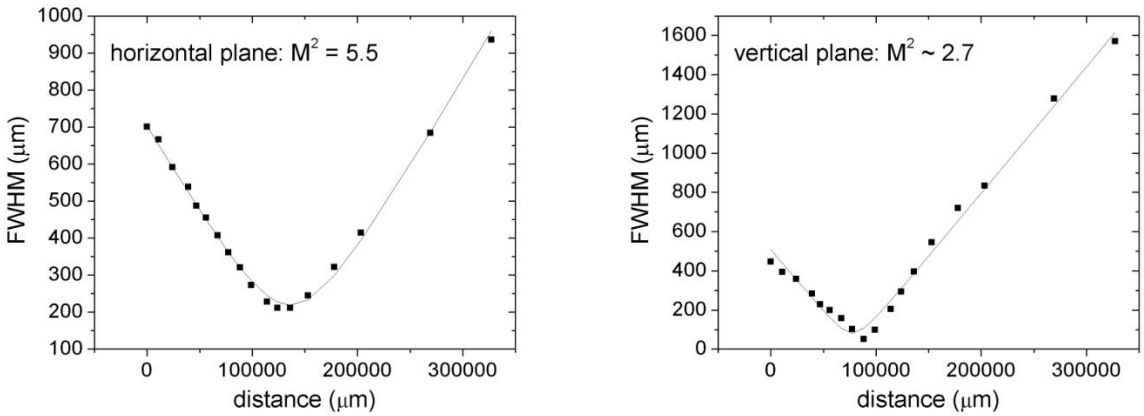

Fig. 8: Measurement of M^2 value of the output of the blue diode laser.

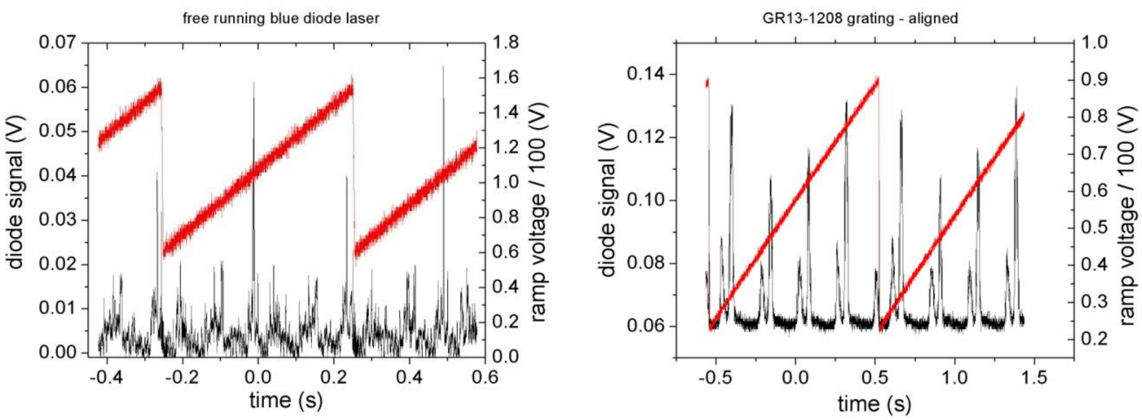

Fig. 9: Scanning Fabry-Perot images of the free running (left) and diode laser and the external (grating) cavity blue diode laser (right).

After the grating, about 285 mW of power was available to the experimental setup. The beam after the grating was circularized using a pair of anamorphic prisms pairs. After the anamorphic prism pair, a half-wave plate was used to rotate the horizontally polarized diode beam into vertical polarization. A spherical lens of focal length 500 mm was used to roughly match the laser and the ring cavity modes. The ring cavity consisted of plane mirrors M1, M2 and curved mirrors M3 and M4 of radius of curvature 75 mm. The length of the external ring cavity was ~780 mm: the distance between the focusing mirrors was typically 84-85 mm, the distances between the focusing and the flat mirrors were both ~196 mm, and the distance between the flat mirrors was ~305 mm. The diode laser beam was coupled into the cavity through M1, which had 98% reflectivity so as to have optimal coupling. The cavity enhancement was monitored by the leakage through the mirror M2. Leakage powers of ~700 μW and 70 μW were measured parallel and antiparallel, respectively relative to the incoupled beam. The antiparallel beam arose from back reflection at the BBO crystal surface indicating that the AR coatings were not according to specification (0.25%). We estimate that the field enhancement was not larger than a factor of two, which is considerably below the theoretical estimates. The reasons will be explained below. A 10-mm long (5x5x10 mm^3), type-I BBO cut at $\theta = 64.6^o$ and AR coated at the fundamental and SH wavelength was used as the SHG crystal. The crystal was placed between mirrors M3 and M4 at the location of the beam waist of the cavity mode. The UV output was coupled out using the partially transmitting (at 223 nm) mirror M4 and was sent to a spectrophotometer. Figure 10 shows the measured diode laser output and the UV output.

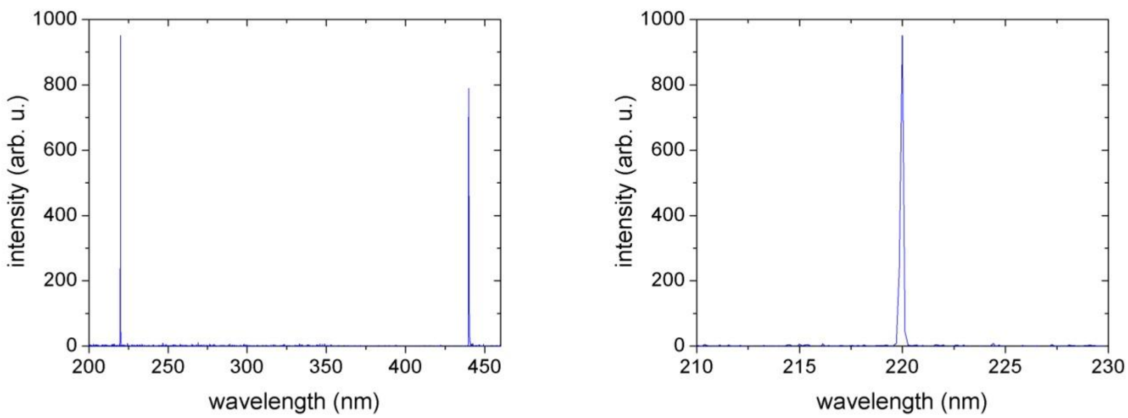

Fig. 10: Fundamental and second harmonic (UV) output using cavity enhanced SHG (left), and generated UV output spectrum (right).

The relatively large power circulating antiparallel to the incoupling power is likely a result of Brillouin scattering [6] and the associated feedback into the diode laser. This was not expected from BBO and our relatively low power levels. The backscattered (phase-conjugated) signal forces the diode laser to emit a mode that is matched to the external optics. This makes the feedback even more efficient. A distinct change in the diode laser beam profile was observed due to this feedback. It should be mentioned that a simple back-reflection off a glass plate outside the diode laser did not results in a noticeable change in the diode laser output. The feedback effect can severely affect the coupling into the external cavity and the frequency conversion efficiency. We recently acquired a Faraday isolator to mitigate the problem. This component arrived at the end of the 9-month period of this project and we have not yet tested its usefulness.

Conclusions

We have generated UV (220 nm) output by cavity enhanced frequency doubling of a cw diode laser operating at 440 nm. Pump laser transverse and longitudinal modes were characterized. Modeling results predict ~30 mW of UV output achievable from second harmonic conversion of 250 mW of 440 nm for ideal Gaussian beams. The experimentally observed output power of a few μW does not reach the theoretical values due to few shortcomings of the present setup, which are currently being addressed. These issues are:

(i) Feedback provided by the grating is too low. We could not find a vendor to AR coat the Nichia diode laser and therefore a larger than what was anticipated feedback factor is required. An external cavity end mirror retro-reflecting the 1st diffraction order of the grating improved the feedback ratio and the beam parameters considerably. This should also improve the single-mode emission of the diode laser.
(ii) The beam parameters of the diode laser were not up to specs. A more elaborate mode matching optics needs to be designed to match both the horizontal as well as the vertical beam waist onto the cavity mode.
(iii) An improved dichroic mirror with high transmission at 220 nm should be used. It was ordered and will arrive within the next 6 weeks.
(iv) The model described above is valid for ideal (M=1) Gaussian beams and needs to be modified to take into account of beam ellipticity.
(v) The coupled cavity needs to be re- designed taking into account the realistic diode beam parameters.

We will address these issues starting in May with an undergraduate student in a summer project. Because of delays in the arrival of the diode laser (custom order) these problems could not be solved during the 9-month period of the project.

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